DEVELOPING NEW CHEMICAL-RHEOLOGICAL MODELS AND CHEMICAL-DURABILITY INDICES OF BITUMEN

MADI HERMADI
HF-080011

A thesis submitted in
fulfilment of the requirement for the award of the
Doctor of Philosophy

Faculty of Civil and Environmental Engineering
Universiti Tun Hussein Onn Malaysia

NOVEMBER, 2013

DEDICATION

I dedicate this work to my beloved parents:
Mr. Ambia Robandi Padliwinata & Mrs. Deetje Helena Tiodora Paulana (alm)

Also to my beloved wife and children:

- Ika Rostika
- Zikri Rachman
- Fikri Fauzi Rahman
- Ziyan Adilah Rahmah
- Zahra Farida Rahmah

To my youngest brother who has supported me:

- Mr. Yadi Hermayadi

To my superior who I respect:

- Ir. Irman Nurdin (alm)
- Assoc. Prof. Dr. Kemas Ahmad Zamhari
- Ir. Nono, M.Eng.Sc.

ACKNOWLEDGEMENTS

Firstly I would like to thank Allah for His blessings and for helping me to achieve success in every endeavour of my life. I really was very grateful and would like to take this opportunity to say thank you very much to my supervisor, Professor Dr. Ahmad Tarmizi bin Abdul Karim and Associate Professor Dr. Kemas Ahmad Zamhari for their support and guidance throughout the entire duration of my study. This research would have certainly been much more difficult without their expertise and knowledge on the subject.

In particular, I would like to express my gratitude to the Institute of Road Engineering, and the Experimental Station for Material and Road Pavement of Indonesia for allowing me to carry out this PhD project and for their financial support.

ABSTRACT

Significant correlation among chemical properties, rheological characteristics and durability of bitumen is very important in evaluating and modifying bitumen. However, a number of previous studies found inconsistent correlation. Therefore, a study on developing new chemical-rheological models and chemical-durability indices was carried out. Two bitumen fractionation method, Rostler and Corbett methods were used to extract each chemical fraction of bitumen. A number of experiments were conducted to evaluate the effect of each chemical fraction on bitumen rheology such as the effect of asphaltenes, polar aromatics, naphthene aromatics, nitrogen bases, first acidaffins, second acidaffins and paraffins on elastic modulus (G'), viscous modulus (G") or fatigue factor (G*sin[δ]), and rutting fator (G*/sin[δ]). Two bitumen from different sources, namely Petronas petroleum bitumen and Buton rock asphalt (BRA) bitumen, were used. New chemical-rheological models were formulated to estimate the bitumen rheology in corporating parameters which are G', G" or (G*sin[δ]), and (G*/sin[δ]) based on the chemical properties. Furthermore, new chemical durability indices that may indicate the ageing rate of bitumen during short-term and long-term ageing were also formulated. Based on statistical analyses, the models and the indices, which were developed by using chemical properties according to Rostler method were found to be invalid because the real and the predicted rheology were significantly different. While according to Corbett method the models and the indices were valid because the differences is not significant since t-score of the models and the indices were maximum 2.679 and 2.119 or less than t-critical 2.797 and 2.861 respectively). The novelties of this study are the new models and the new indices can be used to predict the bitumen rheology and ageing rate based on the chemical composition. Furthermore, they are very important as guides in modifying a bitumen chemical composition to produce a bitumen mixture with the desired rheology and short-term or long-term ageing rate.

ABSTRAK

Korelasi yang signifikan antara sifat kimia, ciri reologi dan ketahanan bitumen adalah sangat penting dalam menilai dan mengubahsuai bitumen. Walau bagaimanapun, beberapa kajian sebelum ini mendapati bahawa korelasi ini adalah tidak konsisten. Oleh itu, satu kajian mengenai pembangunan model baru reologi-kimia dan indeks ketahanan-kimia bitumen telah dijalankan. Dua kaedah pemeringkatan bitumen, iaitu kaedah Rostler dan Corbett telah digunakan untuk mengekstrak setiap bahagian kimia bitumen. Beberapa percubaan telah dijalankan untuk menilai kesan setiap bahagian kimia terhadap reologi bitumen seperti kesan *asphaltenes*, *polar aromatics*, *naphtene aromatics*, *nitrogen bases*, *first acidaffins*, *second acidaffins* dan *paraffins* kepada modulus elastik (G'), modulus kelikatan (G"), factor ubah bentuk ($G^*\sin[\delta]$) dan factor aluran ($G^*/\sin[\delta]$). Dua bitumen dari sumber yang berbeza, iaitu bitumen petroleum Petronas dan asphalt batu Buton (BRA), telah digunakan. Model baru reologi-kimia telah dirangka untuk menganggar ciri-ciri reologi bitumen, seperti G', G" atau $G^*\sin[\delta]$, dan $G^*/\sin[\delta]$ berdasarkan sifat kimia. Di samping itu, indeks ketahanan kimia baru yang menunjukkan kadar penuaan bitumen semasa jangka pendek dan jangka panjang penuaan juga telah dirangka. Berdasarkan analisis statistik, model dan indeks yang dibangunkan dengan menggunakan sifat-sifat kimia mengikut Rostler tidak sah kerana reologi sebenar dan yang diramalkan berbeza secara ketara. Manakala menurut kaedah Corbett, model dan indeks tersebut adalah sah kerana perbezaan sebenar dan yang diramalkan tidak ketara atau t-skor model dan indeks adalah maksimum 2,679 dan 2,119 atau kurang dari pada masing-masing t-kritikal 2,797 dan 2,861. Penemuan ini merangkumi model dan indeks baru yang boleh digunakan untuk meramalreologi dan indeks ketahanan bitumen berdasarkan ciri-ciri kimia. Tambahan pula, penemuan ini juga adalah sebagai panduan dalam mengubahsuai bitumen untuk menghasilkan campuran dengan ciri-ciri reologi dan kadar penuaan jangka pendek atau jangka panjang yang dikehendaki..

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A	Asphaltenes
A_1	First acidaffins
A_2	Second acidaffins
AI	Ageing Index
BBR	Bending Beam Rheometer
BRA	Buton Rock Asphalt, that natural rock asphalt from Buton Island
CDI	Chemical Durability Index
CDI-I	Chemical Durability Index based on Rostler fractionation method
CDI-II	Chemical Durability Index based on Corbett fractionation method
cP	Centi Poises
CSS	Creep Strain Slope
DSR	Dynamic Shear Rheometer
DTT	Direct Tension Test
ESALs	Equivalent single axle loads
δ	phase angle
FID	Fame Ionization Detection
FTIR	Fourier Transforms Infrared Spectroscopy
G’	Elastic modulus
G”	Viscous modulus
G*	Complex shear modulus
$G^*/\sin[\delta]$	Rutting factor to indicate rutting susceptibility
$G^*\sin[\delta]$	Fatigue factor to indicate fatigue susceptibility
G_{mm}	Maximum specific gravity
GR	Gotolski Ratio

H_2SO_4	Sulfuric acid
85% H_2SO_4	Glover sulfuric acid
98% H_2SO_4	Concentrated sulfuric acid
H_2SO_4+SO_3	Fuming sulfuric acid
$H_2S_2O_7$	Fuming sulfuric acid
HP-GPC	High Performance Gel Permeation Chromato-graphy
HMA	Hot mix asphalt
HMAC	Hot mix asphalt concrete
Hz	Hertz
I.E.C.	Ion Exchange Chromatography
I_A	Asphalten Index
I_G	Gastel Index
I_C	Colloidal Index
IDT	Indirect tension
ITFT	Indirect Tensile Fatigue Test
ITSM	Indirect tensile stiffness modulus
Kabungka BRA	Buton Rock Asphalt from Kabungka region
kPa	Kilo Pascals
Lawele BRA	Buton Rock Asphalt from Lawele region
Long-term ageing	Ageing of bitumen during asphalt pavement construction and in service
MP	Melting point
N	Nitrogen bases
N_i	Gyration numbers at initial compaction
N_d	Gyration numbers at design compaction
N_{max}	Gyration numbers at maximum compaction
OBC	Optimum bitumen content
P	Paraffins
$Pa \cdot S$	Pascal Second
PAV	Pressure Ageing Vessel that used to simulate long-term ageing condition of bitumen
PAV-aged	After long-term ageing that simulated by PAV
PG	Performance Grade

POBC	Predicted optimum bitumen content
RDR	Rostler Durability Ratio
RTFOT	Rolling Thin Film Oven Test that used to simulate short-term ageing condition of bitumen
RTFOT-aged	After short-term ageing that simulated by RTFOT
RV	Rotational Viscometer
SARA	Saturates, Aromatics, Resin and Asphaltene
SGC	Superpave Gyratory Compactor
Short-term ageing	Ageing of bitumen during construction of asphalt pavement
SHRP	Strategic Highway Research Program
T	Maximum applied torque,
TFOT	Thin Film Oven Test that used to simulate short-term ageing condition of bitumen
Tg	Glass transition temperature
TLC	Thin Layer Chromatography
TSR	Tensile strength ratio
UTM	Universal Testing Machine
UV	Ultraviolet rays or electromagnetic radiation with a wavelength shorter than that of visible light, but longer than X-rays
VMA	Voids in Mineral Aggregate
W_c	Work dissipated per load cycle,
τ	shear stress
γ	shear strain response
τ_{max}	Maximum applied shear stress
γ_{max}	Maximum response shear strain
σ_o	Applied stress
$\in_0$	Strain
R	Radius of specimen
θ	Deflection (rotation) angle
H	Height of specimen
S(t)	Creep stiffness at the time

REFERENCES

Adhikari, S. & You, Z., (2010), *Fatigue Evaluation of Asphalt Pavement using Beam Fatigue Apparatus*, the Technology Interface Journal.

Affandi, F., (2012), *The Performance of Bituminous Mixes Using Indonesia Natural Asphalt*, Proceeding of 25th ARRB Conference, Perth, Australia.

Ahmed, N. G. & Ismail, N. M., (2009)., *Comparative Evaluation For Mix Design of Marshall and Superpave Methods*. Journal of Engineering and Development, ISSN 1813-7822, 13(2), 1–20.

Anderson, D.A. & E.L. Dukatz (1980), *Asphalt Properties and Composition: 1950-1980*, Proceedings, Association of Asphalt Paving Technologists, Vol. 49, 1-29.

Airey G. D., (1997), *Rheological Characteristics of Polymer Modified and Aged Bitumens*, University of Nothingham: Thesis Ph.D.

Airey, G. D., Mohammed, M. H., (2008), *Rheological properties of polyacrylates used as synthetic road binders*, Springer.

Arora, M. G., Kennedy, T. W., (1997), *SHRP Asphalt Binder Specifications for Saudi Environment,* the Road Construction Rehabilitation and Maintenance Session of the XIIIth IRF World Meeting, Toronto, Ontario, Canada

Asi, I. M. (2007). Performance evaluation of SUPERPAVE and Marshall asphalt mix designs to suite Jordan climatic and traffic conditions. *Construction and Building Materials*, *21*, 1732–1740.

Asphalt Institute & Eurobitume, (2011), *The Bitumen Industry – A Global Perspective Production, chemistry, use, specification and occupational exposure,* Second Edition, USA.

Attanasi, E. D. & Meyer, R. F., (2007), *Natural Bitumen and Extra-Heavy Oil*, World Energy Council, London.

Behrens, M. W., Dot, T., Biehler, A. D., Dot, P., Brown, L. L., Dot, M., Canby, A. P., et al. (2006). *NCHRP - Volumetric Requirements for Superpave Mix Design*. TRB, WASHINGTON, D.C.

Bell, C. A., (1989), *Summary Report on Aging of Asphalt-Aggregate Systems*, Oregon State University, Corvallis.

Berkers, R. F. A., (2005), *Influence of Chemical Composition on the Performance of Bitumen*, Department of Civil Engineering – Tswane University of Technology: Master Thesis

Breen, J. J., Stephens, J. E., (1967), *The Glass Transition Temperature and the Chemical Properties of Asphalt*, Annual Conference of the Canadian Technical Asphalt Association, Victoria.

Boyer, R.E., (2000), *Asphalt Rejuvenators "Fact or Fable", Asphalt Institute*, Texas.

Jones, B. & Nachtsheim, C. J., (2009), *Split-Plot Designs: What, Why, and How*, Journal of Quality Technology Vol. 41, No. 4.

Brown, E. R., Kandhal, P. S., & Zhang, J. (2001). *Performance Testing for Hot Mix Asphalt, NCAT Report 01-05*. Center for Asphalt Technology, Auburn University, Alabama.

Brownridge, J., (2010), *The Role on Asphalt Rejivenator in Pavement Preservation: Use and Need for Asphalt Rejuvenation*, Tricor Refining, LLC, Bakersfield, California United States.

Castaño, N., Ferré, P., Fossas, F., & Puñet, A., (2004), *A Real Heat Bitumen Antistripping Agent*, Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa (CAPSA'04) ISBN Number: 1-920-01718-6

Chen, X., & Huang, B. (2008). *Evaluation of moisture damage in hot mix asphalt using simple performance and superpave indirect tensile tests*. Construction and Building Materials, 22(9), 1950–1962.

Cheng, Y., Bi, H., Gong, Y., Jiano, Y., & Yang, X. (2011). *Comparative research on Superpave Gyratory Compaction method and Marshall Compaction method in the mix design of AC-16.* Proceedings 2011 International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE), 2383–2385. doi:10.1109/TMEE.2011.6199700

Chiu, C. T., & Chiu, Y. H., (2008), *Study of Aging Characteristics of Recycled Asphalt Binders: Focusing on the Chemical Properties*, Chinese Society of Pavment Engineering Journal Vol 1 No.1.

Corbett, L.W., (1969), *Composition of asphalt based on generic fractionation using solvent deasphalting, elution-adsorption chromatography, and densimetric characterization*, Analytical Chemistry, Vol. 41, pp. 576-579, 1969.

Demirabs, A., (2002), *Asphaltene yields from five types of fuels via different methods*, Energy Conversion and Management 43 1091–1097

Deputy Minister of Energy and Mineral Resources, (1999), *The Recommendation to Improof BRA Utilization*, Coordinating Minister for Economy, Finance, and Industry, Jakarta.

Directorate General of Highway, (2009), *Interim Special Specification section 6.3 of Hot mix asphalt of BRA-Lawele*, Ministry of Public Work, Jakarta.

European Asphalt Pavement Association (EAPA) and the National Asphalt Pavement Association (NAPA), (2011), *The Asphalt Paving Industry: A Global Perspective*, Brussels, Belgium.

Guern, M. L., Chailleux, E., Farcas, F., Dreessen, S., & Mabille, I., (2010), *Physico-chemical analysis of five hard bitumens: Identification of chemical species and molecular organization before and after artificial aging*, Fuel Journal.

Hamzah, M. O., Shahadan, Z., (2011), *Effects of Aging on the Physical, Rheological* *and Chemical Properties of Virgin Bitumen Incorporating Recovered Reclaimed Asphalt Pavement Binder*, Australian Journal of Basic and Applied Sciences.

Hardee, J. R., (2004), *Physical and Chemical Characteristics of Superpave Binders Containing Air Blown Asphalt*, Henderson State University Arkansas: Final Report MBTC 2049.

Hermadi, M., Syahdanulirwan, M., (2005), *Correlation of Durability Index with Durability of Bitumen*, Road and Bridge Journal Vol.22 N0. 3, 2005" Ministry of Public Work, Bandung.

Hermadi, M., Syahdanulirwan, M., (2008), *Proposed Specification of Hot Mix Asphalt using BRA-Lawele as a binder*, Road and Bridge Journal, Ministry of Public Work, Bandung.

Houston, W. N., Mirza, M. W., Zapata, C. E., Raghavendra, S., (2005), *Environmental Effects in Pavement Mix and Structural Design Systems*, NCHRP Project 9-23 Part-1, 2005.

Hrdlicka, G. M., Tandon, V., Prozzi, J., Smit, A., Yildrim, Y., (2007), *Evaluation of Binder Tests for Identifying Rutting and Cracking Potential of Modified Asphalt Binders*, Center for Transportation Infrastructure Systems, The University of Texas, El Paso.

Hudson,W. R., & Kennedy, T. W., *An Indirect Tensile Test for Stabilized Materials,* Research Report 98-1, Center for Highway Research, The University of Texas at Austin,January 1968.

Isacsson, U. & Zeng, H., (1997), *Relationships between bitumen chemistry and low temperature behaviour of asphalt*, Construction and Building Material, Vol. 11, No. 2, 83-91.

Jabatan Kerja Raya, (2008), *Standard Specification for Road Work Section 4: Flexible Pavement*, JKR/SPJ/2008-S4, Kuala Lumpur, Malaysia.

Jitsangiam, P., Chindaprasirt, P., & Nikraz, H., (2013), *An evaluation of the suitability of SUPERPAVE and Marshall asphalt mix designs as they relate to Thailand's climatic conditions*, Elsivier Journal of Construction and Building Materials,

Jones, B., Nachtsheim, C. J., (2009), *Split-Plot Designs: What, Why, and How*, Journal of Quality Technology, Vol. 41, No. 4,

Juraideh, A., (2010), *A Study on Moisture Induced Damage and Rutting of Hot Mix Asphalt*, Universiti Teknologi Mara: Thesis Ph.D.

Kamaruddin, I. (2008). *Fatigue Behaviour of Fibre Reinforced Bituminous Mixtures from Indirect Tensile Fatigue Test*, Universiti Teknologi Petronas, Malaysia.

Kamboozia, N., Arabani, M., (2012), *The Linear Visco-Elastic Behaviour of Glasphalt Mixture Under Dynamic Loading Conditions,* Proceding of 25th ARRB Conference, Perth, Australia.

Kandhal, P. S., Cooley, L. A., (2001), *The Restricted Zone in the Superpave Aggregate Gradation Specification*, NCHRP Report 464, National Center for Asphalt Technology, Auburn University, Aubun.

Khan, K. M., & Kamal, M. A. (2008), Impact of Superpave Mix Design Method on Rutting Behavior of Flexible Pavements in Pakistan. *The Arabian Journal for Science and Engineering, Volume 33, Number 2B*, *33*(2), 379–390.

Kramers, J. W., Goel, P., (1989), *Final Report Volume 2 of Asbuton Resources of Buton Island*, Alberta Research Council, Canada.

Kumar, S. A., Krishnan, J. M., Veeraragavan A., (2009), *Steady Shear Properties of a Class of Aged Bitumens*, Efficient Transportation and Pavement Systems-Al-Qadi, Alnuami and Masad (eds).

Lesueur, D.,(2009), *The Colloidal Structure of Bitumen: Consequences on the Reology and on the Mechanisms of Bitumen Modification*, Advances in Colloid and Interface Science Journal.

Lu, X. & Isacsson, U., (2002), *Effect of Ageing on Bitumen Chemistry and Rheology*, Construction and Building Materials.

Mallick, R.B., El-Korchi, T., (2009), *Pavement Engineering, Principles and Practice,* CRC Press Web site at http//www.crcpress.com.

Mamlouk, M.S. & Zaniewski, J.P., (2006), *Materials for Civil and Construction Engineers*, Second Edition, Pearson Education, Inc., United States of America.

Mangum, M. (2006), *Asphalt Paving Sector Presentation. Health Effects of Occupational Exposure to Emissions from Asphalt/ Bitumen Symposium*. Dresden, Germany.

Maupin, G. W. J. (1971), *Relationship of Fatigue to the Tensile Stiffness of Asphaltic Concrete*. Virginia Highway Research Council and the U So Department of Transportation Federal Highway Administration, Virginia.

Michalica, P., Kazatchkov, I. B., Stastna, J., Zanzotto, L., (2008a), *Relationship between chemical and rheological properties of two asphalts of different origins*, Fuel 87 (2008) 3247–3253.

Michalica, P., Daucik, P., & Zanzotto, L., (2008b), *Monitoring of Compositional Changes Occurring During The Oxidative Aging of Two Selected Asphalts from Different Sources*, Petroleum and Coal ISSN 1337-7027, 2008.

Ministry of Public Work, (2006), *Guide line for Building and Construction – Book 1 General of BRA Utilization*, Ministry of Public Work, Jakarta.

Montepara, A., Giulani, F., (2001), *Variation in Chemical and Rheological Properties of Bitumen Due to Aging Action*, Departement of Civil Engineering, University of Parma, Italy.

Meyer R. F., & Witt W., (1990), *Definition and World Resources of Natural Bitumens*, U.S.A.: Geological Survey Bulletin No. 1944.

Meyers, M., Chawla, K., (2009), *Mechanical Behaviour of Materials,* Second edition, Cambridge University Press, Cambridge.

Muniandy, R., & Aburkaba, E. (2011). *The effect of type and particle size of industrial wastes filler on Indirect Tensile Stiffness and Fatigue performance of Stone Mastic Asphalt Mixtures*. Australian Journal of Basic and Applied Science, ISSN 1991-8178, 5(11), 297–308.

National Highway Institute, (2009), *Superpave Fundamentals Reference Manual*, Federal Highway Administration, U.S. Department of Transportation.

Nazar, A. R. S. & Bayandory, L. (2008), *Investigation of Asphaltene Stability in the Iranian Crude Oils*, Iranian Journal of Chemical Engineering Vol. 5, No. 1 (Winter), 2008, IAChE

NCHRP, (2011), *Report 673 - A Manual for Design of Hot Mix Asphalt with Commentary*, Transportation Research Board, Washington, D. C.

Okogu, B. E., (2003), *The Middle East and North Africa in a Changing Oil Market,* International Monetary Fund, http://www.imf.org/external/pubs/ft/med/2003/eng /okogu /okogu.htm

Osman, S. A. (2004). *The Role of Bitumen and Bitumen/Filler Mortar in Bituminous Mixture Fatigue*, Ph.D. Thesis, Department of Civil Engineering, The University of Nottingham.

Oyekunle, L. O., (2005), *Influence of Chemical Composition on the Physical Characteristics of Paving Asphalts*, Proceding of 2nd Mercorus Congress on Chemical Engineering and 4th Mercorus Congress on Process Systems Engineering, Rio de Janeiro.

Oyekunle, L. O., (2006), *Certain Relationships between Chemical Composition and Properties of Petroleum Asphalts from Different Origin*, Lagos:Oil and Gas Science and Technology Vol. 61.

Portland Cement Association, (2009), The Monitor Flash Report of Paving, the New Realities, USA.

Petersen, J. C., (1982), *Relationships between Asphalt Chemical Composition and Performance-Related Properties*, Larami Energy Technology Center, U.S.

Department of Energy, Las Vegas.

Petersen, J. C., (2009), *A Review of the Fundamentas of Asphalt Oxidation*, Transportation Research Board (TRB), Washinton D.C.

Polacco, G., Kriz, P., Filippi, S., Stastna, J., Biondi, D., Zanzotto, L., (2008), *Macromolecular Nanotechnology Rheological properties of asphalt/SBS/clay blends*, European Polymer Journal 44 3512–3521.

Putman, B. J., & Amirkhanian, S. N. (2006). *Laboratory Evaluation of Anti-Strip Additives in Hot Mix Asphalt, Report No. FHWA-SC-06-07*. Department of Civil Engineering Clemson University, Clemson.

Qiu, X., Wong, W., & Hu, C., (2009), *Laboratory Performance Evaluation on Polymer Modified Porous Asphalt Concrete*, GeoHunan International Conference on Challenges and Recent Advances in Pavement Technologies and Transportation Geotechnics, Hunan, China.

Read, J. M. (1996). *Fatigue Cracking of Bituminous Paving Mixtures PhD-Thesis*. Department of Civil Engineering, University of Nottingham.

Roberts, F. L., Kandhal, Prithvi, S., Brown, E.Ray, Lee, Dah-Yinn, Kennedy, Thomas W. *Hot Mix Asphalt Materials, Mixture Design and Construction.* NAPA Education Foundation, Lanham, MD. 1996.

Robertson, R. E., (1991), *Chemical Properties of Asphalts and Their Relationship to Pavement Performance*, Washington DC: SHRP-A/UWP-91-51

Romanoschi, S. A., Dumitru, N. I., & Dumitru, O. (2006). *Resilient Modulus and the Fatigue Properties of Kansas Hot Mix Asphalt Mixes*. Kansas State University, Manhatan, Kansas.

Rostler, F. S., (1985), *Fractional Composition: Analytical and Functional Significance*, Sherard and Associates, California.

Sadid, H., Wabrek, R. M., Dongare, S., Coryell, B., & Ebrahimpour, A. (2010). *Materials Acceptance Risk Analysis : Superpave Hot Mix Asphalt*, Idaho

Transportation Department Research Program Division of Highways, Resource Center, Idaho State University.

Shell Bitumen, (1995), *The Shell Bitumen Industrial Handbook ISBN-0-95 16625-1-1*, Shell Bitumen, Surrey.

Shen, J., Amirkhanian, S., Miller, J. A., (2007), *Effects of Rejuvenating Agents on Supperpave Mixtures Containing Reclaimed Asphalt Pavement*, Journal of Materials in Civil Engineering (ASCE).

SHRP-A-417, (1994), *Accelerated Performance-Related Tests for Asphalt-Aggregate Mixes and Their Use in Mix Design and Analysis Sistems*, SHRP National Research Council, Washington DC.

Siddiqui, M. N., (2003), *Alkylation and Oxidation Reactions of Arabian Asphalthenes*, Fuel Elsevier Juornal.

Siswosoebrotho, B. I., Kusnianti, N., Tumewu, W., (2005), *Laboratory Evaluation of Lawele Buton Natural Asphalt in Asphalt Concrete Mixture*, Proceeding of the Eastern Asia Society for Transportation Studies, 2005.

Supriyadi, (1989), *Report of Corring Asbuton in Lawele in Buton Island to Indentify the Asbuton Deposits*, IBRD Highway Maintenace and Betterment Project.

The Freedonia Group, (2012), *World Asphalt Industry Study with Forcests for 2013 & 2018*, USA.

Wang, J. N., Kennedy, T. W., & McGennis, R. B. (2000). *Volumetric and Mechanical Performance Properties of Superpave Mixtures*, Journal of Materials in Civil Engineering (1), 238–244.

West, R. C., Watson, D. E., Turner, P. A., Casola, J. R., (2010), *Mixing and Compaction Temperatures of Asphalt Binders in Hot-Mix Asphalt*, NCHRP Report 648, Transportation Research Board, Washingtn D.C.

Xiao, F., Amirkhanian, S. N., Putman, B. J., & Juang, H. (2012). *Feasibility of Superpave gyratory compaction of rubberized asphalt concrete mixtures* *containing reclaimed asphalt pavement*. Construction and Building Materials, *27*(1), 432–438.

Xue, Y., Hou, H., Zhu, S., & Zha, J. (2009). *Utilization of municipal solid waste incineration ash in stone mastic asphalt mixture: Pavement performance and environmental impact.* Construction and Building Materials, *23*(2), 989–996.

Yapp, M. T., Durrani, A. Z., Finn, F. N., (1991), *HP-GPC and Asphalt Characterization Literature Review*, SHRP, Washington D. C.

Yildirim, Y., Solaimanian, M., & Kennedy, T. W. (2000), *Mixing and compaction temperatures for superpave mixes,* Asphal Paving Technology, 69, 34–71.

Yi-Qiu, T., Jia-Ni, W., Zhong-Liang, F., Xing-Ye, Z., (2007), *Influence and Mechanism of Ultraviolet Aging on Bitumen Performance*, Proceedings of the 26th Southern African Transport Conference (SATC 2007) ISBN Number: 1-920-01702-X, Pretoria, South Africa.

Youtcheff, J. S., & Jones, D. R., (1994), *SHRP-A-686 Guidline for Asphalt Refiners and Suppliers*, Washington DC: SHRP.

Yusoff, N. I. M., Ginoux, M. S., Airey, G. D., Hainin, M. R., (2010), *Modelling the Linear Viscoelastic Rheological Properties of Base Bitumens*, Malaysian Journal of Civil Engineering 22(1).

Zaniewski, J. P. & Kanneganti, V., (2003), *Comparison of 19 mm Superpave and Marshall Base II Mixes in West Virginia*, Final Report, Prepared for the West Virginia Department of Transportation, Division of Highways, in cooperation with the US Department of Transportation, Federal Highway Administration.

Zaniewski, J. P., Padula, M., (2003), *Automation of the Superpave Mix Design Process for the West Virginia Division of Highways*, Asphalt Technology Program, Department of Civil and Environmental Engineering, Morgantown, West Virginia.